A STEM APPROACH TO STANDARD SCIENCE CURRICULUM TOPICS: CHEMICAL REACTIONS AS A TYPICAL EXAMPLE

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Abstract

This study explores the integration of STEM principles into chemistry education through the redesign of the topic Chemical Reactions for initial teacher training. The aim was to develop and evaluate an innovative teaching module that fosters key competences–knowledge, skills, and attitudes—via student-centred, context-based, and interdisciplinary approaches. The research followed a design-based methodology, involving the development, implementation, and iterative refinement of teaching materials. Data were collected through textbook analysis, classroom observations, and pilot feedback from pre-service teachers. Key features of the module include experimental reaction cycles, real-life applications, and the use of digital tools. The findings show that this approach enhances students' conceptual understanding, motivation, and ability to connect chemistry with real-world issues such as sustainability and materials design. The module promotes inclusive and engaging science teaching and serves as a replicable model for other curriculum topics. It also supports the preparation of future teachers for competence-oriented and interdisciplinary education.
Keywords: *STEM education, chemical reactions, curriculum innovation, teacher education, experimental learning*

Introduction

Reforming the traditional curriculum in STEM subjects (science, technology, engineering, and mathematics) is essential to prepare students for a rapidly changing world in which these disciplines play a key role in addressing global challenges such as climate change, sustainability, and health innovation (Duncan, 2010). Modern education should reflect the interconnectedness of these disciplines and promote their practical application. It is essential to transcend traditional boundaries between subjects and enable students to understand the connections between theory and practice across disciplines. Integrating the teaching of mathematics, physics, chemistry, and technology opens up the space for deeper understanding and innovative thinking (Koldová et al., 2024).

At the same time, it is important to emphasise practical skills such as experimentation, working with data, or solving complex problems. Project-based learning and learning based on real-world challenges allow students to acquire the skills needed for today's job market. Creativity, teamwork, and critical thinking are just as important as professional skills today. Teaching approaches should therefore be oriented

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as much as possible towards actively involving students and encouraging them to think independently (Beers, 2011; National Academy of Engineering & National Research Council, 2014; Chroustová et al., 2021).

One of the standard topics in chemistry education that can be suitably transformed using STEM principles is chemical reactions. In the classical approach, these are often presented only as a set of equations or through isolated demonstrations. However, current teaching can enrich this topic with an engineering approach, effective experiments, practical tasks, and a wider overlap with everyday life. Such teaching enables students to better understand the mechanisms of chemical processes and, at the same time, develops their ability to apply the knowledge gained in new situations.

The aim of this study was to address this gap by developing and evaluating an innovative teaching module on chemical reactions designed for pre-service science teachers as one example of the results of the project Erasmus+ STEMkey (Teaching Standard STEM Topics with a Key Competence Approach) (STEMkey, 2023). The module incorporates experimental cycles, real-life applications, and interdisciplinary connections to foster key competences as defined in the European Framework. This paper presents both the theoretical foundations and practical outcomes of implementing the module in initial teacher education.

Research Methodology

General Background

This research is grounded in a design-based research (DBR) approach, which is well-suited for educational innovation and iterative refinement of teaching practices (Trna, 2011). The study focused on transforming the traditionally taught topic of chemical reactions into a STEM-based teaching module for pre-service chemistry and science teachers. The rationale stems from the need to align initial teacher education with current educational challenges, including sustainability, interdisciplinarity, and competence development. The study aimed not only to develop a pedagogically sound curriculum innovation but also to investigate its impact on teaching practices and student engagement.

Sample Selection

The research involved a purposeful sample of 8 chemistry teachers from the practice and 16 pre-service science teachers enrolled in a master's program at the Faculty of Education, Charles University, Czechia. These teachers were selected based on their active participation in chemistry methodology courses and their willingness to engage in curriculum development activities. The sample represents a typical population of future secondary school chemistry teachers in the Czech educational context.

Instruments and Procedures

The research process consisted of three main phases: (1) analysis of existing teaching practices, (2) design and implementation of the new module, and (3) evaluation and refinement based on feedback.

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1. Phase 1 – Needs Analysis
   A qualitative review of chemistry textbooks, curriculum documents, and lesson plans was conducted to identify how the topic of chemical reactions is currently taught. Classroom observations and informal interviews with teacher educators further informed the identification of common shortcomings, such as over-reliance on theoretical instruction and limited hands-on experimentation.
2. Phase 2 – Module Design and Implementation:
   Based on the initial findings, an innovative teaching module was developed. It included structured experimental cycles (e.g., the calcium cycle), real-life applications, interdisciplinary activities, and digital simulations. These elements were embedded in a sequence of learning tasks, scaffolded into three stages: warm-up, immersion, and real-life connection. The module was piloted in seminar settings over two academic terms.
3. Phase 3 – Evaluation and Feedback Collection:
   Teachers' feedback was gathered using interviews, and student future teachers' feedback was gathered using group discussions. Observations of student engagement and performance during activities also served as data sources. Revisions were made to the module after each round of implementation, ensuring it was responsive to user needs and aligned with pedagogical goals.

Data Analysis

Qualitative data were analysed using thematic coding to identify recurring patterns in teachers' and students' feedback and classroom interactions. Particular attention was given to indicators of conceptual understanding, motivation, and perceived relevance of the module. Reflective statements were categorized according to the European Framework of Key Competences, allowing the researchers to map evidence of competence development. Observational notes were used to triangulate self-reported data and validate the findings.

Research Results

The integration of the STEM approach into the topic of chemical reactions in initial teacher education aims to support the development of key competences, defined as a combination of applied knowledge, skills, and attitudes. This approach emphasizes student-centred learning, real-life applications, interdisciplinary links, and the use of digital tools. Through these principles, the teaching of chemical reactions is transformed into a context-based learning experience that reflects current societal and environmental challenges.

Within the proposed module, students explore the principles and consequences of chemical changes as a foundation for understanding natural processes. Central to the approach is the use of *experimental cycles*, where the starting and final substances are the same. These cycles highlight the interconnectedness of chemical processes, their classification, and their relevance to everyday life and sustainability.

Knowledge is acquired through hands-on activities, critical observation, and reflection. Skills are developed in three learning environments–*in vivo* (real-life

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context), *in vitro* (laboratory experiments), and *in silico* (digital simulations and models). These activities foster scientific inquiry, reasoning, and evidence-based decision-making. Attitudes are shaped by encouraging critical thinking, ethical reflection, and environmental awareness.

The proposed curriculum is structured into progressive stages—introductory ("warm-up"), exploratory ("immersion"), and applied ("real-life connection") activities. Students work individually and in groups, participate in discussions, and engage with experimental tasks designed to build understanding and support meaningful application of chemical concepts.

By integrating chemistry with other STEM disciplines—particularly mathematics, engineering, and digital technologies—students not only strengthen their conceptual grasp but also develop the ability to relate scientific content to real-world issues. The ultimate goal is to prepare future teachers to implement chemistry education in a way that is innovative, inclusive, and responsive to the demands of modern society.

For the ambience evocation, we propose a warm-up activity oriented to mapping the field of interest with the title "Chemical reactions and their use in sustainable development". This activity serves to mapping of elected types of chemical reactions in complex social problems – chemical reactions related to production, consumption, and sustainable development – in detailed different contexts. At the beginning of this activity, brainstorming is recommended (with the right setting, time, prohibited words, technical realization, etc.). Central term for brainstorming can be CHEMICAL REACTIONS or different types of chemical reactions or changes of substances, e.g., "REDOX REACTIONS" or "FERMENTATION", etc., or something other with relation to the topic Chemical reactions as self. The next step is clustering; it means the classification of groups of produced words. Students propose groups such as science, economics, politics, culture… The last step is the creation of concept maps in each group of words, and next to create a common concept map about the phenomenon CHEMICAL REACTIONS, connected with discussions about different experiences, mainly with everyday contexts. Notices for brainstorming topic alternatives can be more sophisticate, it means e.g. producing only conditions for chemical reactions (kind of substances, area of industry, agriculture etc.) or producing names or words containing the different word connected with chemical reactions (processes of production, chemical reactions and their examples in different languages etc.). Types of chemical reactions have different connections with other science disciplines and not only with them. A very wide impact have topics such as redox reactions and electricity, complex reactions and pigments, addition reactions and food production, acid-base reactions and volumetric analysis, etc.

For a deeper understanding of the topic Chemical Reaction, we pay attention to so-called reaction cycles in connection with STEM approaches under the title "Conversion of chemicals based on calcium compounds". The concept of experimental cycles meets the trends of increasing students' interest in a traditional and often uninteresting topic, not only by the sheer funny effect of the topic, but also by its interesting content and context. However, some very well-known experimental cycles (e.g., copper cycles) do not meet the requirements for the safety of the work in terms of their implementation in the school laboratory. A feasible experimental cycle seems to be the calcium cycle, which, although less convenient in terms of colour changes and the typology of chemical reactions, meets the safety requirements better and, on the other hand, has very close contacts with practical applications (building and construction materials).

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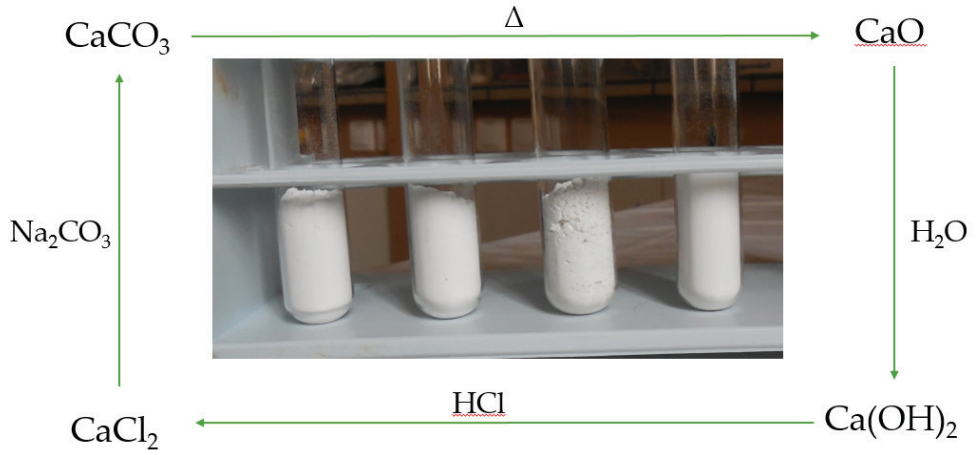
Although the experimental cycles of copper described above meet the requirements for a school chemistry experiment in terms of variability and description possibilities of chemical reactions, the situation is less favourable in terms of safety requirements. For these reasons, the experimental copper cycle can be replaced by the calcium cycle, which, although less favourable in terms of colour changes and also in terms of the typology of chemical reactions, better meets the safety requirements for its use in teaching. In general, information on the experimental calcium cycle can be found in various contexts. For example, the calcium cycle in nature or the process of limestone burning, lime quenching, and mortar solidification are well known in various forms, including practical contexts, especially in the construction and architecture. For the school laboratory, we can design an experimental calcium cycle based on chemical transformations associated with changes in state - solid white substances and colourless solutions. The experimental cycle includes different types of reactions, representing the chemical properties of calcium compounds, and shows the interrelationship of chemical transformations, characteristic of this element and other elements of the same group (e.g., magnesium). In this context, we propose to implement the cycle shown in Figure 1. It is a cycle consisting of four sub-steps:

1. Thermal decomposition of calcium carbonate
2. Reaction of calcium oxide with water
3. Reaction of calcium hydroxide with hydrochloric acid
4. Reaction of calcium chloride with sodium carbonate.

Figure 1
Experimental Calcium Cycle



Note: from left, calcium carbonate, calcium oxide, calcium hydroxide, calcium chloride (STEMkey, 2023)

The first two reactions represent chemical decomposition and chemical fusion, the next is an acid-base reaction, and the last is a precipitation reaction that leads to a product identical to the starting substance of the cycle. The cycle thus represents the major basic types of reactions of inorganic substances. The actual performance of the

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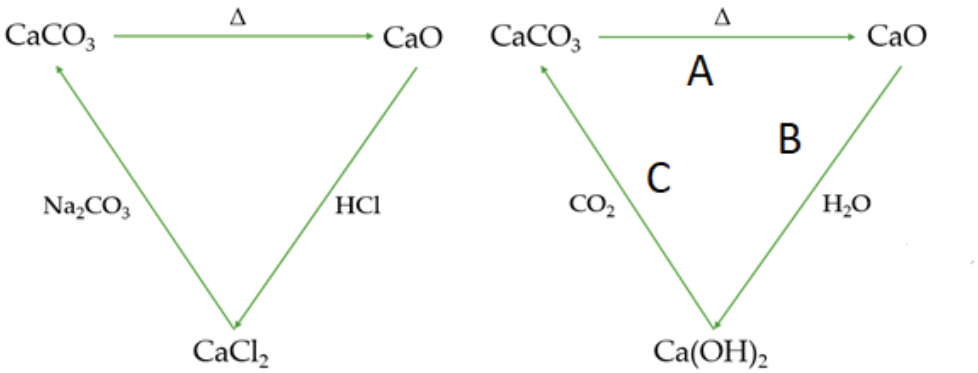
individual reactions is possible with basic chemistry laboratory equipment, even in elementary schools, and with available chemicals. The partial decomposition of calcium carbonate or the low solubility of calcium hydroxide in water, for example, should be taken into account when implementing a set of reactions, which can also be a stimulus for creative discussion. Simpler variants derived from the previous cycle are shown in Figure 2, which shows two cycles.

Figure 2
Basic Cycle Alternatives – Calcium



Note. STEMkey, 2023

The first one shows a set of reactions: thermal decomposition of calcium carbonate, reaction of calcium oxide with hydrochloric acid, and reaction of calcium chloride with sodium carbonate. This is a classic method of converting limestone to pure calcium carbonate (production of pure calcium carbonate for the cosmetics, food, and paper industries). The second cycle (the thermal decomposition of calcium carbonate, the reaction of calcium oxide with water, and the reaction of calcium hydroxide with carbon dioxide) focuses on a familiar theme - the burning of limestone (A), the extinguishing of lime (B), and the solidification of mortar (C). Each reaction is accompanied by a series of tests to demonstrate the presence of starting materials and products in the reaction mixture.

The cycle on the right side of Figure 4 directly links to various building materials, and its use in project-based learning is suggested. Thus, in the creation of different materials from concrete or mortar that can be used in the daily life of the school or its surroundings (see Figure 3).

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Figure 3

Examples of Concrete Outdoor Furniture as Products of a School Project Oriented to the Improvement of the School Garden

Source: https://www.tzb-info.cz/rozhovory-komentare/16072-betonove-designove-stoly-ve-skolni-zahrade-vznikly-diky-iniciative-rodicu

Experimental activity connected with the calcium cycle focuses on interdisciplinary connection mainly in project applications (concrete outdoor furniture, concrete art creations, mortar products, analysis, and using construction (smart) materials, etc.

Application tasks in the topic Chemical Reaction offer various examples from different areas of everyday life. One example deals with the engineering aspects of a funny experimental activity with the title "How to prepare material with specific properties?". The STEM appropriate way to teach chemical reactions is to show them in action and, based on the possibilities, let students get hands-on with exploring the reactions. One of the main questions concerning used materials is their properties. Hands-on activities nearby chemical reactions can provide students with these experiences. Students will define criteria and constraints for creating a new material as part of the engineering process, look for a change in properties to see whether a chemical reaction occurs, and a new substance is formed, and know that chemical reactions create new materials.

The preparation of new materials with specific properties involves chemical reactions based on different starting materials. A suitable funny example can be the so-called slime, which is often found in entertaining chemistry shows. The different properties of slime will require students to apply the engineering reasoning and design process to plan, create, and test their slime product. They will need to reason and decide

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on providing the desired properties of their slime and then experiment to find the most appropriate process for its preparation (recipe).

The activity will begin by identifying a suitable procedure to prepare the slime (some students can have an experience with slime creation). There are well-known procedures using the so-called "white school glue," or it is possible to use flour or other substances. Each procedure, which is best done in groups, is discussed with the teacher to ensure safety and availability of the necessary starting materials. The chemical principle of slime production is also discussed (crosslinking of polymers).

First, it is possible to vary the slime preparation procedure to obtain different slime products. For example, use a larger or smaller amount of one of the starting substances (e.g., contact lens solution if a procedure using it is used). A so-called "fluffy" slime can also be made, for example, by using an appropriate amount of shaving foam instead of water, etc. The next steps are focusing on preparing slime with specific properties. It can be e.g.: shimmering slime (adding glitter), magnetic slime (adding iron filings), glowing slime (adding glowing colour), slime changing colour based on temperature change (adding thermochromic pigment), glow-in-the-dark slime (adding e.g., tonic drink), slime reacting to the pH of the environment (adding an acid-base indicator, e.g., red cabbage juice), etc.

Production of materials with different properties is one of the main objectives of engineering activity or engineering thinking. In connection with the phenomenon, chemical reaction is an important example of STEM education. Chemical reaction, physical condition for realisation, and different next connections as biological, mathematical, or environmental, have to be in account.

Figure 4

Samples of Slime as the Products of STEM-Oriented Chemical Experiment at Elementary School

Source: https://staryweb.zsnizbor.cz/clanky/art/58/34/SLIZ-ve-skole

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Discussion

The findings of this study suggest that integrating a STEM-based approach into the teaching of chemical reactions significantly enhances pedagogical outcomes in initial teacher education. In particular, the use of experimental cycles and context-rich, interdisciplinary activities promotes conceptual understanding, learner engagement, and competence development across cognitive and affective domains (Rychtera & Bílek, 2018; Vondrová & Rendl, 2015).

These results align with previous research emphasizing the benefits of inquiry-based and context-oriented teaching in science education. For example, the work of Trna (2011) and the National Research Council (2012) highlights the importance of connecting scientific content with real-world applications to improve students' motivation and relevance perception. The current study builds upon these foundations by offering a specific and replicable model of how such integration can be implemented in chemistry teacher training.

The use of experimental cycles, such as the calcium cycle, is especially noteworthy. While previous studies (e.g., Condike, 1975; Todd & Hobey, 1985; Walker et al., 2012) have shown the educational value of reaction cycles like the copper cycle, our research contributes by identifying and testing a safer and more applicable alternative for classroom use. The calcium cycle not only maintains the pedagogical strengths of circular processes (Duesing, 1985; Luna Vera et al., 2018; Royal Society of Chemistry, 2015) but also better meets safety and feasibility criteria, as discussed in the work of Kolář et al. (2018; 2019).

Moreover, the structure of the teaching module—scaffolded into warm-up, immersion, and real-life connection phases—supports diverse learning styles and reinforces the pedagogical principles of differentiation and inclusion (Beers, 2011). These aspects are consistent with contemporary approaches that emphasize student agency, collaboration, and creativity in STEM learning (National Academy of Engineering & NRC, 2014).

In contrast to traditional instruction methods, often criticized for their abstractness and limited transferability (Rychtera & Bílek, 2018), this study shows that curriculum innovation grounded in STEM integration allows for the transformation of even conservative topics into engaging and meaningful learning experiences. The inclusion of "in vivo", "in vitro", and "in silico" components further supports multimodal learning and reflects broader pedagogical trends aimed at blending hands-on, experimental, and digital learning environments (Chroustová et al., 2021).

In terms of theoretical contribution, this study offers a concrete example of how competence-based education frameworks (COM, 2019) can be operationalized in subject-specific teacher training. By integrating practical applications, ethical reflection, and interdisciplinary connections, the module fosters the development of transversal competences that are increasingly demanded by modern education systems (Schneider, 2016; STEMkey, 2023).

In summary, the present study not only confirms findings from earlier research but also extends current knowledge by providing a systematically designed, evaluated, and adaptable model for chemistry education within the STEM paradigm. It serves as a bridge between theoretical recommendations and practical implementation in teacher education, offering guidance for future curriculum development and educational policy.

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Conclusions and Implications

The findings of this study confirm that the implementation of a STEM-based approach to the standard taught topic of chemical reactions can bring significant improvements to initial science teacher education. Through curriculum innovation grounded in design-based research, we have developed a model that supports deeper conceptual understanding, engagement with real-world issues, and development of transversal key competences. The use of experimental cycles, context-based learning and interdisciplinary integration has proven to be both pedagogically effective and practically feasible in school settings.

One of the most important implications of this work is the confirmation that even traditional topics, often perceived as abstract or difficult, can be transformed into engaging learning experiences. By applying inquiry-based methods, incorporating real-life applications and allowing space for student creativity, future teachers are better prepared to address the diverse needs of their students and to support their development as active, competent, and responsible citizens.

The proposed teaching module can serve as a replicable model for the redesign of other curriculum topics in chemistry and beyond. The integration of "in vivo", "in vitro," and "in silico" approaches illustrates the flexibility of the STEM framework in accommodating different learning styles and technological opportunities. This adaptability is crucial for modern classrooms, which require both innovation and inclusivity.

Furthermore, the results indicate the importance of preparing future teachers not only in subject content, but also in pedagogical strategies that are in line with contemporary educational challenges, such as sustainability, digitalisation, and interdisciplinary problem solving. Embedding these elements into teacher education ensures that graduates are ready to implement forward-looking and meaningful science teaching in their future careers.

The presented approach contributes to bridging the gap between academic science education and practical teaching demands. Its broader application could foster a more integrated, responsive, and competence-oriented model of STEM education that is aligned with the societal expectations of the 21st century.

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Declaration of Interest

The authors declare no competing interest.

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